FURTHER READING

Page ***, 'Relaxation digital-to-analogue converter', P.S. Crovetti, R. Rubino and F. Musolino.

breaking the boundaries between analogue and digital

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Analogue integrated circuits do not take advantage of CMOS technology scaling and are fast becoming a bottleneck in terms of cost and performance of nanoscale integrated systems. Considering this, it has sometimes been wondered if analogue circuits are still necessary in the digital era. The common answer is that analogue circuitry will be always needed, at least in interface circuits exchanging information with an intrinsically analogue physical world.

However, deeper insight reveals that the physical world is less "intrinsically analogue" than it appears at first glance: matter is made up of atoms and molecules, which are discrete entities, fundamental physical quantities like electromagnetic radiation and electric charge are quantized and even in biological systems, information is transmitted in the form of discrete pulses. In other words, it appears more and more that a discrete, i.e. digital, underlying structure lies beneath our everyday analogue experience.

Indeed, based on Claude Shannon's information theory, information is itself discrete in nature. The engineering applications for computation and communication of this key result was one of the intuitions which started the digital revolution. But Shannon's results do not apply just to computers and communications, but to any signal and system at any level of abstraction, down to the physical level: time-varying electrical quantities processed by "analogue" devices, sensors and integrated circuits like operational amplifiers and voltage references are no exception.

Taking fully into account the discrete nature of information at the electrical level means giving up the familiar concept of "continuous-time, continuous-amplitude" analogue signals - which would carry an infinite amount of information at each single instant and are for that reason highly unrealistic - and paves the way to a completely different approach in the design of interface blocks of integrated circuits.

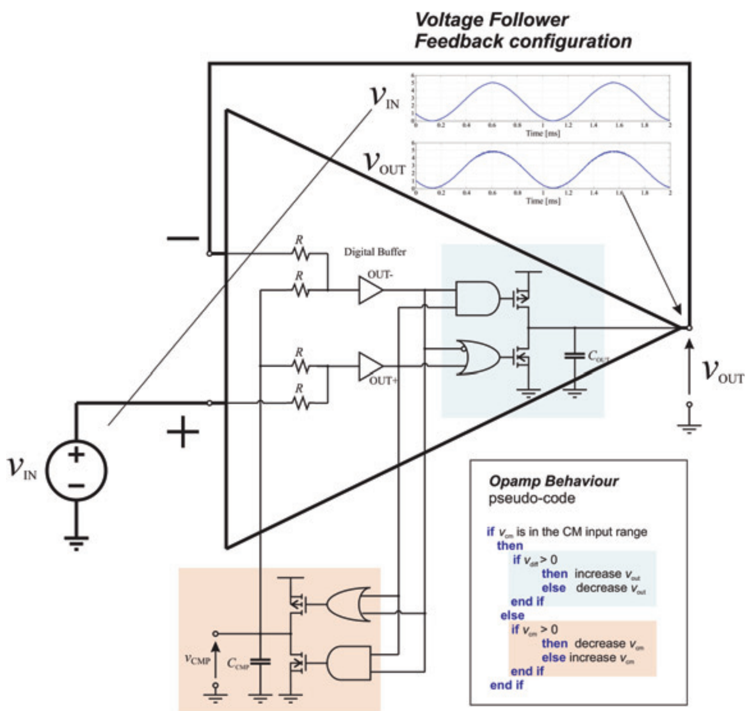


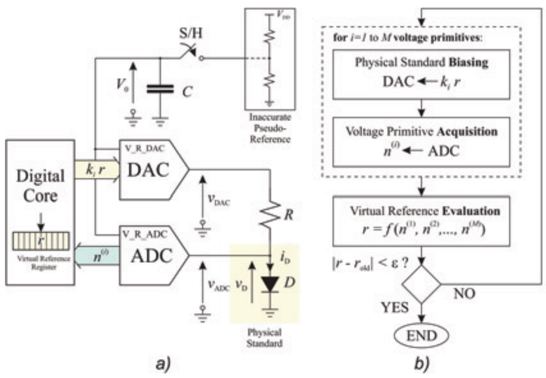
Image: From left to right: Roberto Rubino (MS Thesis Student), Dr. Orazio Aiello (Research Assistant and Marie Sklodowska Curie Fellow), Eng. Pedro Toledo (PhD Candidate), Prof. Paolo S. Crovetti, and Prof. Francesco Musolino.

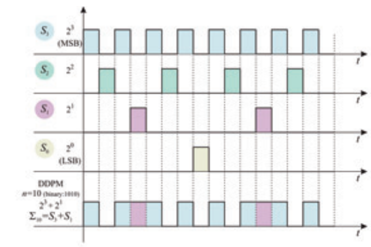
Figure 1: Digital based operational amplifier.

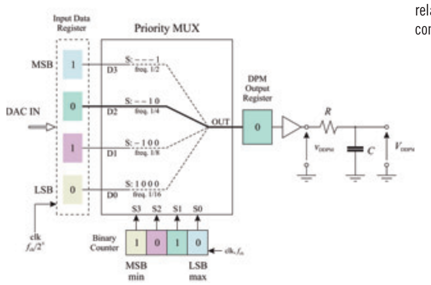
What has been achieved thus far

In the above scenario, our research group at the department of Electronics and Telecommunications (DET), Politecnico di Torino, Italy, has since 2013 been trying to address present-day challenges on analogue interfaces in nano-electronic integrated systems from a novel perspective. Our goal is to develop digital circuits which can be programmed to directly interact with the physical world at the electrical level, grasping relevant information from the environment and providing electrical outputs suitable to be directly applied to physical systems for practical purposes. In other words, our aim is to "translate" physical-level analogue functions into digital so that they can be implemented by true digital integrated circuits, which take full advantage of technology feature size and power supply voltage scaling, robustness to mismatch and process variations, fully automated synthesis, layout, testing and re-configurability.

The possibility to literally "translate" into digital the function of operational amplifiers and voltage references, which can be regarded as the most "analogue" building blocks, has already been addressed. In addition, the feasibility of a "digital based" operational amplifier [1], made up just of true logic gates with a two-level output (i.e. not exploiting the analogue characteristics of digital gates), as shown in Fig.1 and of a microprocessor-based







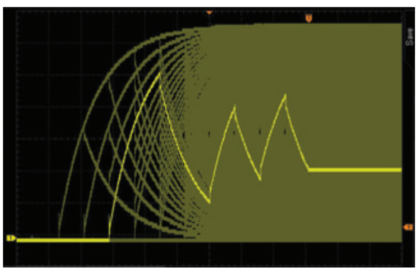


Figure 2: In a virtual voltage reference [2], the functionality of a process-supply-temperature independent voltage reference is implemented in software. **Figure 3**: Dyadic Digital Pulse Modulation [4-5] associates to an integer *n* a bit stream with "analogue-like" features using very simple digital hardware. **Figure 4**: Finely quantized, analogue-like voltage levels obtained by a fully digital relaxation digital to analogue converter.

"virtual voltage reference" [2-3], where a process, supply and temperature independent voltage is obtained algorithmically starting from a possibly inaccurate pseudo-reference (see Fig.2) has been demonstrated on the basis of theory and of proof-of-concept prototypes. The same concepts are still being refined and investigated with promising results in terms of power consumption at very low supply voltage and are well suited to Internet of Things (IoT) applications.

At the same time, our research at the boundaries between the analogue and the digital world have led to the development of Dyadic Digital Pulse Modulation (DDPM) [4]. DDPM is a deterministic digital modulation that associates to a fractional number a digital stream as illustrated in [4] and in Fig.3. The time average of such a stream over increasingly long intervals approximates the number with an increasingly high resolution, resulting in time-resolution trade-off very similar to the time-energy uncertainty observed while measuring signals from the physical world.

From an application perspective DDPM streams have unique "analogue-like" features, which make them well suited to the fully digital synthesis of high-resolution signals, to be exploited in digital control of power electronic convertors, in RF applications, as well as for data conversion. An integrated DDPM digital-to-analogue (D/A) converter with dynamic energy-quality scaling and graceful performance degradation has been recently proposed in a joint project in cooperation with the Green IC Group, led by Professor Massimo Alioto, National University of Singapore (NUS) [5].

Following the same track, the relaxation digital to analogue conversion approach has been devised to obtain finely quantised amplitude levels starting from binary-weighted digital words by using a plain shift register and taking advantage of the exponential impulse response of a first order RC network as in Fig.4. Thanks to this approach, mismatch insensitive, highly efficient digital to analogue converter can be developed as illustrated in this issue [6].

Present and future perspectives

The results achieved so far and those which are expected from ongoing research strongly suggest that "re-thinking" electrical level interfaces towards the physical world in digital terms is feasible, and practically necessary to address the challenges of ultra-low voltage, ultra-low power, highly reconfigurable, low cost acquisition front-ends, power management systems and RF modules for emerging IoT applications.

On the other hand, working midway between analogue and digital suggests that the boundary between the two domains is increasingly blurred and progressively disappearing when the information content of practical signals is concerned, and possibly either an "analogue" or a "digital" point of view could be interchangeably adopted to describe the same phenomena at best. This suggests that not only can digital concepts be applied to analogue systems, but also analogue signal processing concepts could be conveniently applied address the present day challenges of massively parallel neuromorphic computation systems as those required in present day artificial intelligence applications, thus effectively breaking the traditional boundaries between analogue and digital in favour of an unified, cross-domain novel approach to future information processing.

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